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# THE SHAPES OF SOME MOUNTAIN PEAKS IN THE CANADIAN ROCKIES

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## ABSTRACT

Different mountain shapes in sedimentary sequences in the Canadian Rockies were enhanced by glacial erosion and have been modified postglacially by gravity-driven slope processes. Slope modification by both glacial erosion and postglaciation landslides is related to rock structure, particularly bedding dip, rock mass strength and slope geometry. Five mountain peak shapes in monoclinal sequences each fall into different ranges of bedding dips. Castellate (1) and matterhorn (2) mountains occur in sub-horizontal beds and their slopes on all sides follow combinations of bedding planes and joints. The overall slopes are generally 37 to 65° and oblique to both bedding and joints. Slopes in sub-horizontal beds may be controlled by their rock mass strength. Cuestas (3) develop in gently to moderately dipping beds. Dip slopes and steeper, normal escarpments form their cataclinal and anaclinal sides respectively, with the dihedral angle between them about 90°. Hogbacks (4) in moderately to steeply dipping beds have similar slope angles on both cataclinal and anaclinal slopes. Cataclinal slopes are either dip slopes or underdip slopes but anaclinal slopes are often steepened escarpments; the dihedral angle between the slopes is usually less than 90°. Dogtooth (5) mountains occur in steeply dipping to sub-vertical beds and the dihedral angle can be as low as 60°. Slope gradients in inclined beds are closely related to landslides, whose modes are controlled by bedding dips. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: mountain; Canadian Rockies; castellate; cuesta; dogtooth; hogback; landslide; matterhorn

## INTRODUCTION

Geomorphic classifications of mountain types 'generally . . . employ a nomenclature which recognizes the dynamic process that conditions the gross geometry of the relief, rather than using the geometry itself' (Fairbridge, 1968, p. 751). In such 'a simple genetic system of mountain types', the Canadian Rockies would be described as 'Fold and Nappe Mountains: of linear, often with more or less bilateral, symmetry' (Fairbridge, 1968, p. 752). They are 'fold mountains, typical of younger orogenic belts' (Fairbridge, 1968, p. 753). We are going to discuss some of their shapes.

The relationship between the shape of mountains in the Canadian Rockies and their rock structure was first noted in Hector's reconnaissance (Palliser, 1863). Baird (1962, 1963, 1968) described nine different mountain shapes: castellate mountains, matterhorn mountains, mountains in dipping sediments, dogtooth mountains, sawtooth mountains, synclinal mountains, anticlinal mountains, mountains of complex structures and irregular mountains (Baird, 1963, p. 43). Bird (1980, p. 222), Gerrard (1990, p. 20) and Pole (1992, p. 16) all reproduced Baird's (1963) shapes of the Canadian Rockies in their books.

In this paper, we first describe the physical environment of the Rocky Mountain peaks. We then classify the slopes developed in these sedimentary rocks by the angle between the slope and the dip of bedding. This allows us to suggest typical landslide modes on these slopes. We then compare these predictions with the

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shapes of the small sample of peaks described by Baird and with a larger sample selected from the extensive descriptive literature on the Rockies.

Baird's (1962, 1963, 1968) catalogue of mountain shapes made no explicit reference to earlier descriptions of mountain shape from Europe. However, his reliance on rock structure in the catalogue echoes structural geomorphologists (Tricart, 1974) and there is abundant evidence (Cruden and Hu, 1996; Sauchyn *et al.*, 1998; Selby, 1993, Ch. 15) that rock structure strongly influences slope movement processes. The control that rock structure exerts over modes of landsliding is our explanation for the relationship between mountain shape and rock structure in four of Baird's shapes – castellate, matterhorn, dogtooth and mountains of dipping sedimentary rocks.

Understanding the relationship between mountain shape, rock structure and landslides is of practical significance in avoiding potentially hazardous slope movements, siting structures and occupying and using space in mountain areas safely. The study of the development of different mountain shapes and the geological controls upon them also has important implications for mountain and relief development, slope morphology and rock mass transfer in the Canadian Rockies.

## PHYSICAL ENVIRONMENT

The Canadian Rocky Mountains are 100 km wide and extend 1400 km northwestwards from the USA–Canada border 49°N, at 114°W (Mathews, 1986). They are formed by Proterozoic clastics and carbonates, Palaeozoic carbonates and clastics, and Mesozoic clastics (Gabrielse and Yorath, 1992). Late Mesozoic and early Cenozoic thrust faults and folds strike NW–SE in the region. The dominant penetrative discontinuities are bedding planes. 'Discontinuities are here termed penetrative because they are repeated at distances so small compared with the scale of the whole . . . that they can be considered to pervade it uniformly and be present at every point' (Turner and Weiss, 1963, p. 21). There are two common joint sets, both perpendicular to bedding: strike joints are parallel to the strike of bedding, dip joints are perpendicular to it. Conjugate joint sets which are perpendicular to bedding also develop at some locations but are less common than strike joints and dip joints (Muecke and Charlesworth, 1964; Hu and Cruden, 1992a). The strike joints and the conjugate joint sets are kathetal joints, joints 'normal to a bedding surface where the orientation of the joint is a function of the orientation of the bedding' (Hancock, 1964, p. 175). The Canadian Rockies show 'fabric-relief', in which elements of the topographic relief are correlated with the rock fabric (Sander, 1970, pp. 210–212). Most major valleys and mountain ranges follow the strike of the regional geological structures, which are clearly shown in LANDSAT images (Taylor, 1981).

The Canadian Rocky Mountains have experienced several glacial advances over the last two million years; the last glaciation retreated from most of the Rockies as the Holocene began (Clague, 1989) and has left many steep slopes and mountain peaks. Glacially trimmed valleys throughout the Canadian Rockies have slopes of up to 70° towards the mountain peaks. Based on the studies of the cross-profile morphology of glaciated valleys by Hirano and Antya, (1988), particularly their model for the Canadian Rockies, it is reasonable to assume that the crests of valley slopes along most glacially eroded valleys can be steeper than 60° where the rock masses involved are strong enough to maintain such steep slopes.

All the mountain peaks and bedrock slopes discussed in this paper are above the treeline with the base of the bedrock slopes all above 2000 m. Harris (1986) has demonstrated that the lower limit of continuous permafrost is at or above 2400 m (8000 ft) in the Canadian Rockies south of 55°N latitude, i.e. at or above treeline, placing the mountain peaks in the Alpine ecoregion (or zone) (Strong and Leggat, 1992) and the periglacial and glacial morphoclimatic zones of Budel (1982).

## SLOPE CLASSIFICATION BASED ON ROCK STRUCTURE

Slope stability and slope movements in stratified rocks are mainly determined by the orientations of discontinuities within these rock masses and the mechanical properties, particularly frictional properties, of the discontinuities (Selby, 1993, Ch. 15). Slopes in the sedimentary sequences in the Canadian Rockies have been classified into cataclinal slopes and anaclinal slopes where bedding strikes are sub-parallel to the strikes

 

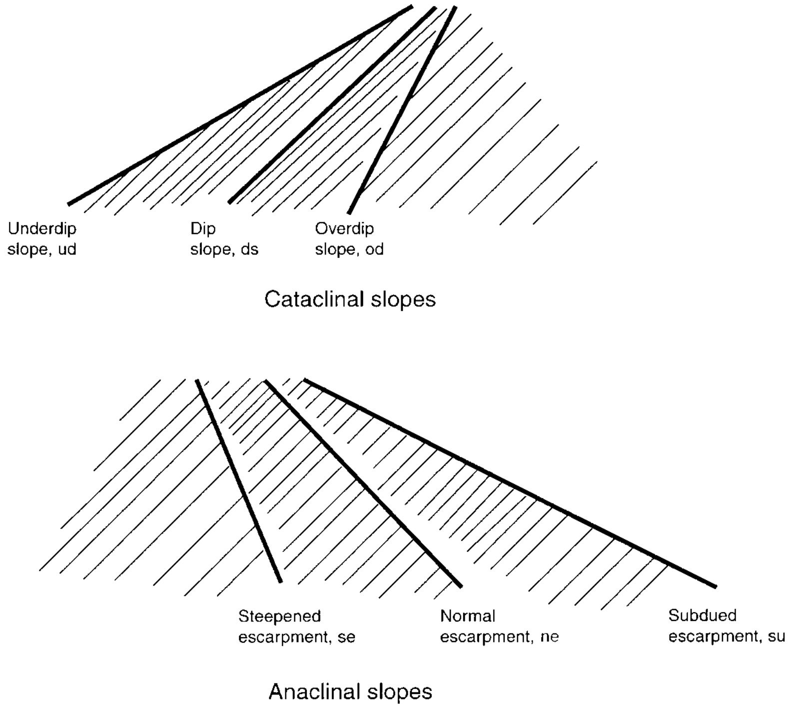


Figure 1. Classification of anaclinal and cataclinal slopes. Thin lines represent bedding, the thick lines indicate slopes. The symbols ud, ds, od, se, ne and su are from Cruden and Hu (1996). The six slopes illustrated are plotted on Figure 2

of the slopes (Cruden and Eaton, 1987, figure 6), using the terms originally introduced by Powell (1875). In cataclinal slopes, the penetrative discontinuity dips in the same direction as the slope. In anaclinal slopes, the penetrative discontinuity dips in the direction opposite to the slope. Conventionally, these descriptive terms can be limited to slopes whose azimuths are within 20° of that of the penetrative discontinuity. Cataclinal slopes may be further divided into overdip slopes which are steeper than the dip of the discontinuity, underdip slopes which are less steep than the dip of the discontinuity, and dip slopes which follow the discontinuity (Figure 1). Anaclinal slopes which are perpendicular to the dip of the discontinuity are called normal escarpments, slopes steeper than normal are steepened escarpments and slopes less steep than normal are subdued escarpments (Figure 1). Studies in Kananaskis Country in the southern Rockies (Cruden and Eaton, 1987, figure 8) found that cataclinal and anaclinal slopes cover 58 per cent of the total slope surface although their slope directions are limited to 80° out of 360°. This evidence of 'fabric-relief' suggests rock fabric controls on slope development.

The landslide modes on cataclinal slopes and on anaclinal slopes are shown on a process diagram (Figure 2). Rapid movements and slow movements (Figure 2) are differentiated to indicate the velocities of the slope processes that modify the mountains. This information is necessary for estimates of how far the displaced material in the landslides will travel.

Cruden and Hu (1996) showed that the modes of the processes depend on the relationships among the orientations of discontinuities, slopes and friction angles of discontinuities. We use the basic friction angles of the discontinuities as estimates of the friction angles. Basic friction angles are measured on planar, sanded rock surfaces (Selby, 1993, table 6:2). The friction angles on these surfaces with no significant roughness are the lower bounds of rapid, unassisted rocksliding in the Canadian Rockies (Cruden, 1985). The basic friction angles of carbonates and clastics range between 21° and 41° (Cruden and Hu, 1988; Hu and Cruden, 1992b), so 30° is a first approximation and is used as the estimate of basic friction angle in Figure 2. Cohesion along bedding in the slopes in the sedimentary sequences in the Canadian Rockies can be ignored in most cases (Cruden and Hu, 1993).

 

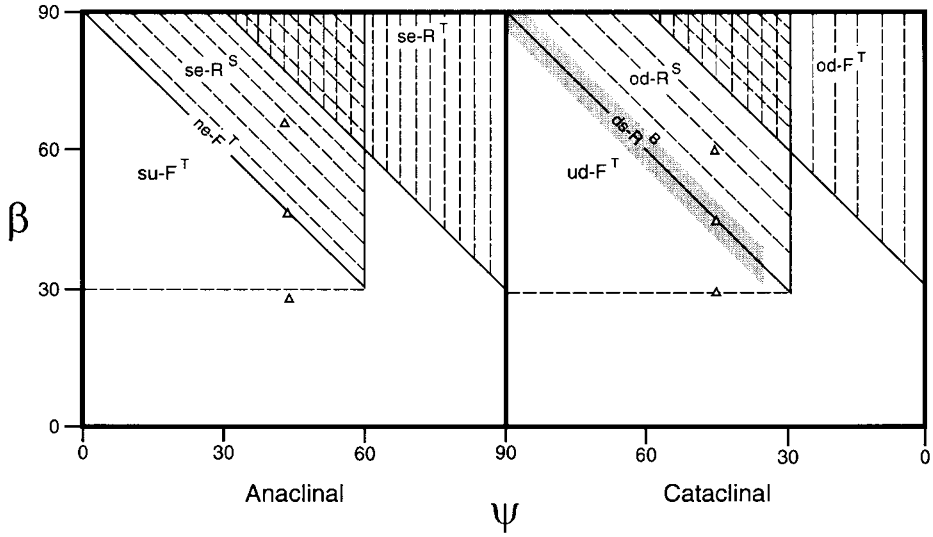


Figure 2. Process diagram for anaclinal and cataclinal slopes. The bedding dip is $\psi$ and the slope angle $\beta$. The symbols su, ne, se, ud, ds and od are defined in Figure 1. The six slopes in Figure 1 are plotted as triangles. Additional symbols: -R and -F denote rapid and slow movements; superscripts T, S and B indicate toppling, sliding and buckling. Symbols follow Howes and Kenk (1988)

Whether, after glacial retreat, rock masses on steep mountain slopes have moved depends on the stability of these slopes in different modes of movement. The volumes of subsequent landslides can be evaluated from the displaced material of rock slides or rock falls. Most large landslides have occurred on cataclinal overdip and dip slopes; the prehistoric ones documented by Cruden (1976) and Evans *et al.* (1997). the 1903 Frank slide (Cruden and Krahn, 1973) and the Brazeau Lake slide of 1933 (Cruden, 1982) are examples. Fragmental rock falls from cliffs have produced talus cones and aprons which are much smaller than rock slide deposits in volume. Other processes including fluvial erosion and dissolution of carbonates are all less significant than landslides in modifying rock slopes (Luckman, 1981; Luckman and Fiske, 1997). So rock slopes in the Canadian Rockies have generally remained almost unchanged in the Holocene except where landslides have occurred.

## CHARACTERISTICS OF DIFFERENT MOUNTAIN SHAPES

Tables I and II list 34 mountains in monoclinal sequences, including their bedding dips and slope gradients. The tables detail nine mountains that Baird (1962, 1963, 1968) used as examples and list a further 25 mountains that have been much photographed; we have obtained structural data from published geological maps, or estimated them from photographs if no geological maps are available. The slopes are obtained from 1:50 000 topographic maps; horizontal distances are directly measured and vertical distances read from the contour lines. The vertical differences are always the first 150 to 200 m down from the peaks. The dihedral angle between the anaclinal and cataclinal slopes on a mountain is estimated by the supplement of the sum of the slope angles. The locations of the mountains are listed in gazetteers (Energy, Mines and Resources, 1974, 1985) and in the references given in Tables I and II.

Baird's (1963) mountain shape classification puts these mountains into the following groups.

### *Castellate mountains*

'Mountains that are cut into more or less flat-lying sedimentary rocks have profiles in which vertical steps alternate with flat or sloping terraces. Some such mountains look very much like ancient castles and are thus

 

Table I. Examples of mountain peak shapes

| Mountains | Shape | Geological map | Illustration |
|---|---|---|---|
| Castle Mountain | Castellate | Mountjoy and Price, 1972b | Baird, 1968p.9 |
| Mt Babel | Castellate | Price *et al.,* 1980a | Putnam, and Boles, 1973 p.157 |
| Mt Edith Cavell | Castellate | Mountjoy and Price, 1988 | Baird, 1963 p.108 |
| Mt Geikie | Castellate | Mountjoy and Price, 1988 | Baird, 1963 p.146; Kruszyna, and Putnam, 1985 p.253 |
| Mt Quadra | Castellate | Price *et al.,* 1980a | Putnam, and Boles, 1973 p.157 |
| Mt Stephen | Castellate | Price *et al.,* 1980b | Baird, 1962 p.37 |
| Mt Temple | Castellate | Price *et al.,* 1980a | Putnam, and Boles, 1973 p.181; Boles *et al.,* 1979 p.275 |
| Pilot Mountain | Castellate | Price and Mountjoy, 1972 | |
| Stanley Peak | Castellate | Price *et al.,* 1978 | Putnam, and Boles, 1973 p.143; Boles *et al.,* 1979 p.221 |
| Mt Assiniboine | Matterhorn | Leech, 1979 | Baird, 1968 p.19 |
| Mt Bowlen | Matterhorn | Price *et al.,* 1980a | Putnam, and Boles, 1973 p.157 |
| Mt Ida | Matterhorn | McMechan and, Thompson, 1995 | Kruszyna, and Putnam, 1985 p.310 |
| Mt King George | Matterhorn | Leech, 1979 | Putnam, and Boles, 1973 p.59 |
| Mt Little | Matterhorn | Price *et al.,* 1980a | Putnam, and Boles, 1973 p.157 |
| Mt Sir Douglas | Matterhorn | Leech, 1979 | Putnam, and Boles, 1973 p.66; Boles *et al.,* 1979 p.73 |
| Mt Tuzo | Matterhorn | Price *et al.,* 1980a | Putnam, and Boles, 1973 p.170 |
| Neptuak Mtn | Matterhorn | Price *et al.,* 1980b | Putnam, and Boles, 1973 p.174 |
| Mt Bogart | Cuesta | McMechan, 1993 | Putnam, and Boles, 1973 p.79: Kane, 1992 p.61 |
| Mt Sparrowhawk | Cuesta | McMechan, 1993 | Kane, 1992 p.88 |
| Sunwapta Peak | Cuesta | | Baird, 1963 p.94 |
| Mt Birdwood | Hogback | Leech, 1979 | Putnam, and Boles, 1973 p.79 |
| Mt Engadine | Hogback | McMechan, 1993 | Putnam, and Boles, 1973 p.79 |
| Mt Foch | Hogback | McMechan, 1993 | Putnam, and Boles, 1973 p.46 |
| The Fortress | Hogback | McMechan, 1993 | Putnam, and Boles, 1973 p.79 |
| Mt Indefatigable | Hogback | McMechan, 1993 | Cruden and Eaton, 1987 |
| Mt Rundle | Hogback | Price, 1970 | Baird, 1968 p.11 |
| Mt Shark | Hogback | Leech, 1979 | Kane, 1992 p.89 |
| Mt Sarrail | Hogback | McMechan, 1993 | Putnam, and Boles, 1973 p.46 |
| NW Elk Range | Hogback | McMechan, 1993 | Hu and Cruden, 1992a |
| Elpoca Mtn | Dogtooth | McMechan, 1993 | Boles *et al.,* 1979 p.148 |
| Mt Blane | Dogtooth | McMechan, 1993 | Putnam, and Boles, 1973 p.88 |
| Mt Brock | Dogtooth | McMechan, 1993 | Boles *et al.,* 1979 p.148 |
| Mt Edith | Dogtooth | Mountjoy and Price, 1972a | Boles *et al.,* 1979 p.144 |
| Mt Louis | Dogtooth | Mountjoy and Price, 1972a | Baird, 1968 p.12 |

said to be ‘castellate’ or ‘castle’ mountains’ (Baird (1963, pp. 43–44). The mountains occur in sub-horizontal beds. An upper bound of bedding dips at 15°, or about half of the basic friction angle, is the lower limit for sliding of blocks along bedding with water pressures at the ground surface (Selby, 1993, p. 362). The movement mode of the rock masses, toppling from kathetal joints (Figure 3), may need some assistance on anaclinal slopes. Masses toppling and sliding are generally limited in our field observations to individual blocks separated by bedding and joints. Blocks can move only short distances before pore pressures drain. So slope processes are relatively ineffective and postglacial modifications of mountain slopes are not significant.

Rock faces or rock walls follow combinations of bedding and joint surfaces, creating overall slopes which are less steep than the nearly vertical joints. If a set of closely spaced joints extends a considerable distance, a rock face several kilometres long can develop along the joint set as at Castle Mountain (Figure 3).

Because the overall slopes are oblique to both joints and bedding (Table II), slope angles may be predicted by rock mass strength ratings (Selby, 1993, figure 6·13) as structural control is not an overriding factor. Slope angles range from 42 to 64° and dihedral angles from 56 to 89°. Such a wide range of slopes suggests that the considerable range in rock mass strength in these sedimentary sequences may be a determining factor in the slope angles observed (Selby, 1993, Ch. 16).

 

Figure 3. Castle Mountain (from the Collection of the Whyte Museum of the Canadian Rockies, V263/71-4618)

Table II. Examples of mountain slopes

| Mountains | Bedding dip (degree) | Cataclinal slopes (degree) | Anaclinal slopes (degree) | Dihedral angle (degree) | Height (m a.s.l.) |
|---|---|---|---|---|---|
| Castle Mountain | 0–5 | 50 | 45–55 | 75–85 | 2766 |
| Mt Babel | 0–10 | 60 | 64 | 56 | 3101 |
| Mt Edith Cavell | 5–10 | 53 | 52 | 75 | 3363 |
| Mt Geikie | 0–5 | 64 | 45–60 | 56–71 | 3270 |
| Mt Quadra | 0–10 | 53 | 50 | 77 | 3173 |
| Mt Stephen | 0–5 | 46 | 45 | 89 | 3199 |
| Mt Temple | 0–10 | 55 | 45 | 80 | 3543 |
| Pilot Mountain | 5 | 64 | 60 | 56 | 2935 |
| Stanley Peak | 0–10 | 42 | 58 | 80 | 3115 |
| Mt Assiniboine | 0–5 | 50 | 57 | 73 | 3618 |
| Mt Bowlen | 0–10 | 37 | 64 | 79 | 3072 |
| Mt Ida | 0–10 | 57 | 60 | 63 | 3180 |
| Mt King George | 0–10 | 56 | 56 | 68 | 3422 |
| Mt Little | 0–10 | 41 | 50 | 89 | 3140 |
| Mt Sir Douglas | 0–10 | 56 | 51 | 63 | 3406 |
| Mt Tuzo | 0–10 | 55 | 65 | 60 | 3245 |
| Neptuak Mtn | 0–10 | 58 | 65 | 57 | 3237 |
| Mt Bogart | 15–25 | 37 | 50 | 93 | 3144 |
| Mt Sparrowhawk | 25–30 | 30 | 60 | 90 | 3121 |
| Sunwapta Peak | 29 | 29 | 63 | 88 | 3315 |
| Mt Birdwood | 50–60 | 56 | 58 | 66 | 3097 |
| Mt Engadine | 30–35 | 35 | 66 | 79 | 2970 |
| Mt Foch | 30–40 | 42 | 50 | 92 | 3180 |
| The Fortress | 35–40 | 40 | 64 | 76 | 3002 |
| Mt Indefatigable | 45–50 | 50 | 51 | 79 | 2670 |
| Mt Rundle | 30–35 | 30 | 55 | 85 | 2949 |
| Mt Shark | 55–65 | 50 | 60 | 70 | 2786 |
| Mt Sarrail | 30–35 | 35 | 60 | 85 | 3174 |
| NW Elk Range | 65–70 | 38 | 60 | 82 | 2744 |
| Elpoca Mtn | 80–90 | 58 | 60 | 62 | 3029 |
| Mt Blane | 80–90 | 50 | 56 | 74 | 2993 |
| Mt Brock | 80–90 | 60 | 58 | 62 | 2902 |
| Mt Edith | 65–70 | 58 | 59 | 63 | 2554 |
| Mt Louis | 65–70 | 63 | 57 | 60 | 2682 |

 

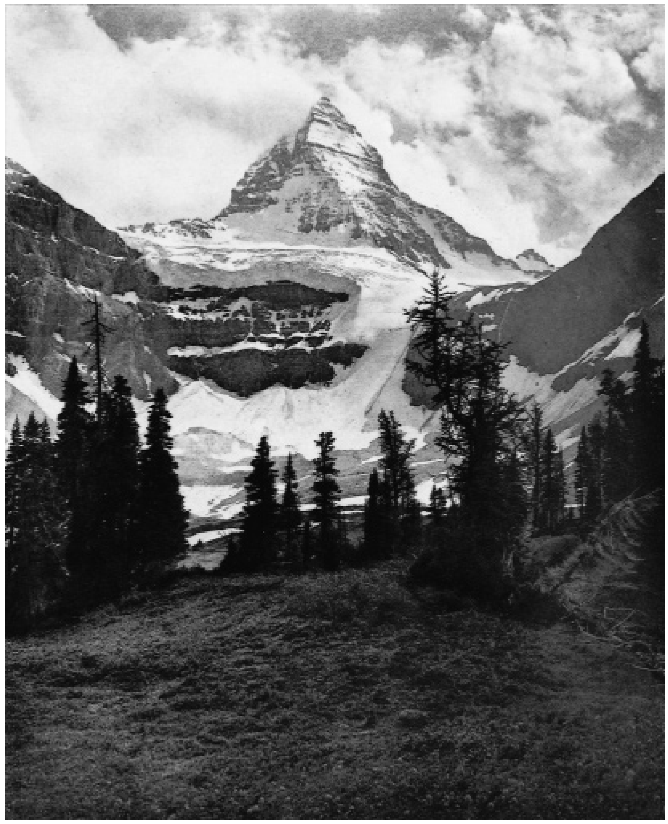

Figure 4. Mount Assiniboine (from the Collection of the Whyte Museum of the Canadian Rockies, NA66-573)

*Matterhorn mountains*

Matterhorns are 'sharp, semi-pyramidal towers' (Baird, 1963, p. 48). The slope processes that create matterhorn mountains are the same as those that form castellate mountains (Figure 2). Erosion develops on all slopes of the matterhorn without a preferred orientation; a distinctive example is Mount Assiniboine (Figure 4), which ascends 750 m at 50° from its shoulders to the peak. We attribute the symmetry of the Matterhorn (Collet, 1927, plate 8) and Mount Assiniboine to the horizontal penetrative discontinuities, foliation and bedding, respectively, that pervade these mountains. The slopes of matterhorns are generally oblique to joints, possibly varying with rock mass strength rating (Selby, 1993, figure 6·13). Like castellate mountains, matterhorns have experienced little modification since the retreat of the last glaciation because large landslides are not kinematically possible. Again, like castellate mountains, the ranges of slope and dihedral angles are large, 37 to 65° and 57 to 89°, respectively (Tables I and II; see also Figure 9).

*Mountains in dipping sedimentary rocks: cuestas and hogbacks*

'Mountains cut in dipping layered sedimentary rocks which dip from nearly horizontal to 60 degrees . . . have one smooth slope which follows the dip of a particular rock layer from its peak almost to its base, and on the other side, a less-regular slope which breaks across the upturned edges of the layered rock units (Baird, 1963, pp. 44–45).

The cataclinal slope of a dipping mountain may follow an individual rock layer from the base to the peak of the mountain (Figure 5). Sliding along bedding can occur either by gravity only or assisted by cleft water

 

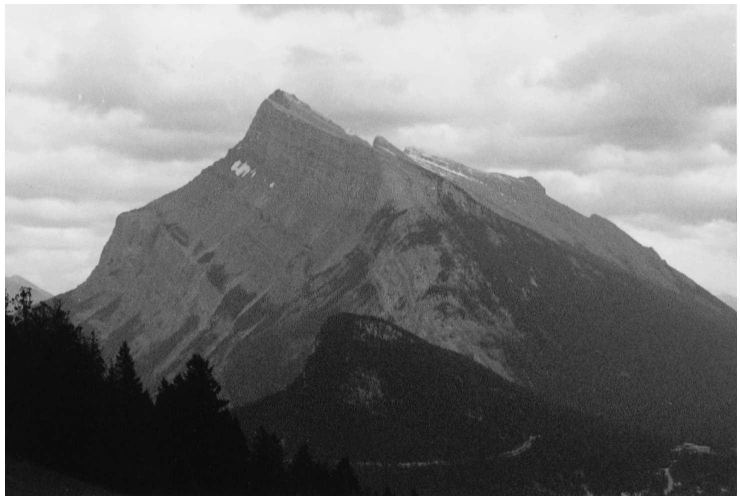

Figure 5. Mount Rundle

pressure, pressure from rocks fallen into joints behind the moving block or ice pressure when bedding dip is less than the friction angle along bedding (Simmons and Cruden, 1980).

On the anaclinal slope, sliding along kathetal joints can occur if the slope is steeper than kathetal joints (Hu and Cruden, 1992a). This process produces normal escarpments on anaclinal slopes. Sliding on anaclinal slopes is generally limited to individual joint-bounded blocks because of the non-penetrative nature of joints, displaced volumes are usually small in single events (Hu and Cruden, 1992a). If the anaclinal slope is less steep than bedding dip, small topples prevail and the slope profile experiences little change.

When a single peak forms, one slope follows bedding from the top to the base (Baird, 1963, p. 44) and the other slopes follow combinations of joints and bedding to form steep scarp slopes. When a long range forms, one side is a dip slope and the other side is usually a normal escarpment. We can divide these mountains into cuestas, whose bedding is less steep than the friction angle, and hogbacks, which have bedding steeper than the friction angle.

The cataclinal slopes on hogbacks are either dip slopes or underdip slopes and the anaclinal slopes are steepened escarpments (Figure 6). The post glaciation processes on cataclinal slopes include sliding along bedding (Figure 2) to create locally steep dip slopes. Rupture surfaces form along bedding and their toes follow joints or faults (Evans *et al.*, 1997). Toppling is a slow process and slopes steepened by glaciation remain little changed (Cruden and Hu, 1994). Both processes maintain steep cataclinal slopes in the main scarps of the movements.

On the anaclinal slopes of hogbacks, there are also two processes: toppling from bedding and sliding along joints. Toppling from bedding can create rapid topple-slides (Figures 2 and 6) that reduce slope gradients. Field examples show that these slopes, after toppling and sliding, are still steeper than 45°; a typical example is Elk Ridge, Alberta (Hu and Cruden, 1992a, figure 6). Sliding along kathetal joints creates small rock slides (Hu and Cruden, 1992a) when dips of kathetal joints are steeper than 40°, close to the upper bound of the basic friction angles of carbonates and clastics, because joints are not penetrative and joint surfaces can be rough. So both processes can maintain anaclinal slopes at over 45°.

*Dogtooth mountains*

‘Sharp jagged mountains sometimes result from the erosion of masses of vertical or nearly vertical beds of rock. The peaks may be centered on a particularly resistant bed, in which case a tall spine or rock wall may result’ (Baird, 1963, p. 45). A typical example is Mount Louis in Banff National Park (Figure 7).

Sliding along bedding rarely develops on sub-vertical cataclinal slopes. Bedding is steep and cohesion is insufficient for rock masses to remain above a bedding plane after the toe support from glacier ice is removed.

 

Figure 6. Elk Ridge

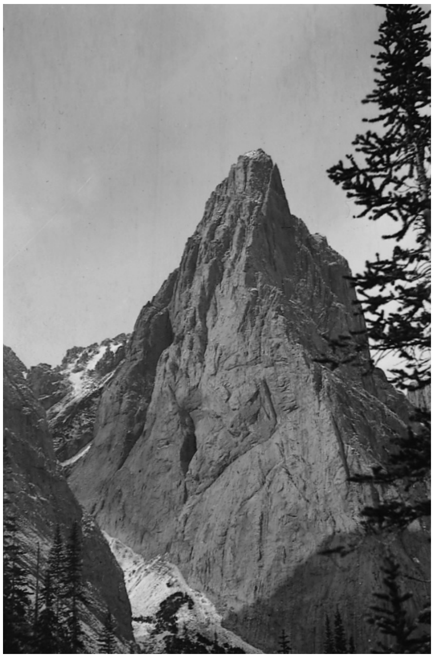

Figure 7. Mount Louis (from the Collection of the Whyte Museum of the Canadian Rockies (V263/71-4477))

Erosion of sub-vertical beds generally produces underdip cataclinal slopes and steepened escarpments. Rock blocks on underdip cataclinal slopes can topple from bedding, a slow process (Figure 2), with assistance from frost heave (McAffee and Cruden, 1996) or pressure from rock debris falling behind the toppled block (Cruden *et al.* 1993). Buckling is also possible (Hu and Cruden, 1993) where slopes are only a few degrees less than bedding dips. Although complex or composite topple-slides are kinematically possible on anaclinal slopes as indicated in Figure 2, none have been reported.

 

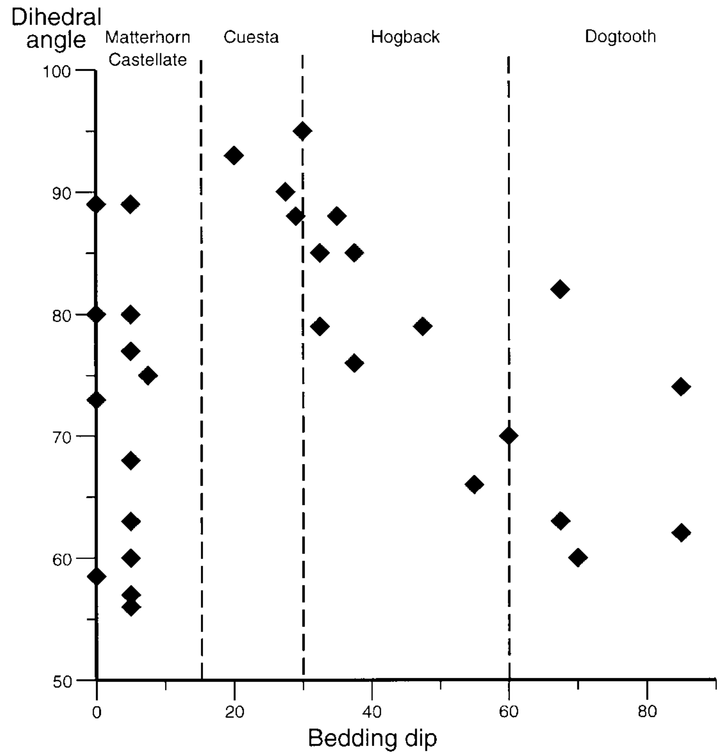


Figure 8. Bedding dip and dihedral angle for the peaks in Tables I and II. Points plotted may be mid-ranges. Coincident points are not distinguished

## DISCUSSION

Structural controls on mountain slope angles can be observed from the relationship of the dihedral angle between the cataclinal and anaclinal slopes and bedding dip (Figure 8). The data are from the mountains listed in Tables I and II. When bedding dips are greater than 15°, Figure 8 shows that the dihedral angle decreases as bedding dip increases. The trend can be explained by Figure 2 which indicates that dip slopes and normal escarpments are characteristic landforms, the results of sliding along bedding and kathetal joints where kinematically possible.

When beds are gently to moderately dipping, between 15 and 60° in Figure 8, the glacially steepened slopes may slide along bedding surfaces and kathetal joints to form dip slopes and normal escarpments. If bedding dips are steeper than 60°, glacially steepened dip slopes, underdip slopes and steepened escarpments have been limited to slopes of about 60°. Buckles (Hu and Cruden, 1993) and topples (Cruden and Hu, 1994) limit cataclinal slopes. Topple-slides have occurred on anaclinal slopes such as the Elk Ridge landslide (Hu and Cruden, 1992a, figure 6). Consequently, the dihedral angles of mountain peaks in steeply dipping beds can be as low as 60° less than those in moderately dipping beds. So, dogtooth mountains are more slender than cuestas.

Structural control by bedding on slopes can also be shown on an overlay (Figure 9) which places all the mountain slopes on the process diagram (Figure 2). When bedding is less than 15°, the dihedral angle (Figure 8) ranges from 55 to 90°, or the slope angle on each side varies from 45 to 62° if the two sides have similar gradients. The slope gradients are not controlled by discontinuity dips. These slopes may be strength-equilibrium slopes (Selby, 1993, figure 6·13). Overdip slopes occur only where bedding dips are less than 15° in our sample, then the rock masses above bedding surfaces may not slide and evolve into dip slopes. When bedding is between 30 and 60°, the characteristic cataclinal slopes are dip slopes which formed as the result of rock sliding from overdip slopes. When bedding is steeper than 60°, underdip slopes develop. On anaclinal

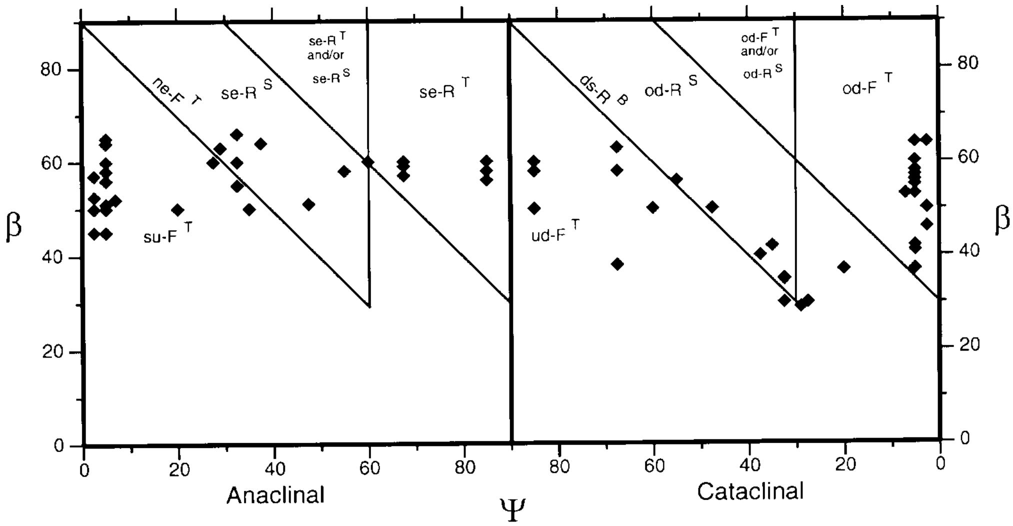


Figure 9. Mountain slopes on the process diagram (Figure 2)

slopes, normal escarpments, the complements of dip slopes, are not as common as dip slopes owing to the non-penetrative nature of kathetal joints.

Comparing the examples of the cataclinal slopes and anaclinal slopes in Figure 9, it is clear that the structural control is more pronounced on cataclinal slopes than on anaclinal slopes. When bedding dip is over 30°, above the basic friction angles of rocks in the Canadian Rockies (Cruden and Hu, 1988; Hu and Cruden, 1992b), most of the glacially steepened overdip slopes have become dip slopes by sliding (Cruden and Hu, 1993). A consistent model suggests that the frequency of rock sliding on overdip slopes was once considerably greater than at present and has decreased over time since the retreat of the last glaciation (Cruden and Hu, 1993). The dip slopes which have resulted from sliding represent stable and characteristic slope forms on cataclinal slopes.

There are many steepened escarpments in Figure 9 where sliding and toppling are indicated as rapid slope processes. Although some large landslides are recorded (Hu and Cruden, 1992a), landslides on the steepened escarpments have not been as frequent as on cataclinal slopes.

The magnitudes of slope processes and mountain slope development have directional preference depending on bedding dips. When bedding is gently to steeply dipping, sliding along bedding and strike joints and toppling from bedding surfaces, all parallel to or opposite to the dip direction of bedding, are the dominant processes. So, mountain ranges generally develop to follow NW–SE trending strikes and cataclinal and anaclinal slopes cover more ground surface than other slopes (Cruden and Eaton, 1987). When bedding is sub-horizontal, slope processes such as toppling from strike and dip joints have no directional preference and isolated peaks or castellate mountains form.

## CONCLUSIONS

Mountain shapes in monoclinal sedimentary sequences in the Canadian Rockies are determined by rock structures and slope movement processes on the glacially steepened slopes. When bedding is steeply dipping to sub-vertical, the dihedral angles between cataclinal and anaclinal slopes can be as low as 60° on dogtooth mountains. When bedding is gently to moderately dipping, sliding on bedding and on kathetal joints creates hogbacks and cuestas whose dihedral angles are about 90°. When bedding is sub-horizontal to gently dipping, the typical mountains are castellate or matterhorns. Half the basic friction angle is the lower limit of the dip of bedding which exerts structural control on slopes. At lower dips, slopes may be in strength equilibrium.

 

Examples show that the critical angles (Figure 2) for landslides on different types of slope are useful in identifying potentially unstable slopes.

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## REFERENCES

Baird, D. M. 1962. *Yoho National Park, the Mountains, the Rocks, the Scenery*, Geological Survey of Canada, Miscellaneous Report **4**, 107 pp.

Baird, D. M. 1963. *Jasper National Park, Behind the Mountains and Glaciers*, Geological Survey of Canada, Miscellaneous Report **6**, 184 pp.

Baird, D. M. 1968. *Banff National Park, How Nature Carved its Splendour*, Geological Survey of Canada, Miscellaneous Report **13**, 307 pp.

Bird, J. B. 1980. *The Natural Landscapes of Canada*, Wiley, Toronto, 260 pp.

Boles, G. W., Kruszyna, R. and Putnam, W. L. 1979. *The Rocky Mountains of Canada–South*, The Alpine Club of Canada, Banff, 473 pp.

Budel, J. 1982. *Climatic Geomorphology*, Princeton University Press, Princeton, New Jersey, 443 pp.

Clague, J. J. 1989. 'Quaternary geology of the Canadian Cordillera'. in Fulton, R. J. (Ed.), *Quaternary Geology of Canada and Greenland*, Geological Survey of Canada, Ottawa, 17–96.

Collet, L. W. 1927. *The Structure of the Alps*, Edward Arnold, London, 289 pp.

Cruden, D. M. 1976. 'Major rock slides in the Rockies', *Canadian Geotechnical Journal*, **13**, 8–20.

Cruden, D. M. 1982. 'The Brazeau Lake slide, Jasper National Park, Alberta', *Canadian Geotechnical Journal*, **19**, 975–981.

Cruden, D. M. 1985. 'Rockslope movements in the Canadian Cordillera', *Canadian Geotechnical Journal*, **22**, 528–540.

Cruden, D. M. and Eaton, T. M. 1987. 'Reconnaissance of Rockslide Hazards in Kananaskis Country, Alberta', *Canadian Geotechnical Journal*, **24**, 414–429.

Cruden, D. M. and Hu X.-Q. 1988. 'Basic friction angles of carbonate rocks from Kananaskis Country', *International Association of Engineering Geology Bulletin*, **38**, 55–59.

Cruden D. M. and Hu, X. Q. 1993. 'Exhaustion and steady state models for predicting rockslide hazards in the Canadian Rocky Mountains', *Geomorphology*, **8**, 279–285.

Cruden, D. M. and Hu, X. Q. 1994. 'Topples on underdip slopes in the Highwood Pass, Alberta, Canada', *Quarterly Journal of Engineering Geology*, **27**, 57–68.

Cruden, D. M. and Hu, X. Q. 1996. 'Hazardous modes of rock slope movement in the Canadian Rockies', *Environmental and Engineering Geosciences*, **2**, 507–516.

Cruden, D. M. and Krahn, J. 1973. 'A re-examination of the geology of the Frank Slide', *Canadian Geotechnical Journal*, **10**, 581–591.

Cruden, D. M., Hu, X. Q. and Lu, Z-Y. 1993. 'Rock toppling at Clairvaux Creek road cut', *Canadian Geotechnical Journal*, **30**, 1016–1023.

Energy, Mines and Resources 1974. *Gazetteer of Canada, Alberta*, Canadian Government Publishing Centre, Supply and Services Canada, Ottawa, Canada, 153 pp.

Energy, Mines and Resources 1985. *Gazetteer of Canada, British Columbia*, Canadian Government Publishing Centre, Supply and Services Canada, Ottawa, Canada, 281 pp.

Evans, S. G., Couture, R., Locat, J., Hadjigeorgiou, J., Antoine, P. and Brugnot, G. 1997. 'Two complex cataclinal slope failures in Paleozoic limestones, Rocky Mountains, Jasper National Park, Alberta', *Proceedings, 50th Canadian Geotechnical Conference*, Ottawa, 20–22 October, Vol. 1, 102–109.

Fairbridge, R. W. 1968. 'Mountain types', in Fairbridge, R. W. (Ed.), *The Encyclopedia of Geomorphology*, Reinhold, New York, 1295 pp.

Gabrielse, H. and Yorath, C. J. 1992. *Geology of the Cordilleran Orogen in Canada*, Geological Survey of Canada, Ottawa, 844 pp.

Gerrard, A. J. 1990. *Mountain Environments: An Examination of the Physical Geography of Mountains*, Belhaven Press, London, 317 pp.

Hancock, P. L. 1964. 'The relations between folds and late-formed joints in South Pembrokeshire', *Geological Magazine*, **101**, 174–184.

Harris, S. A. 1986. 'Permafrost distribution, zonation and stability along the Eastern Ranges of the Cordillera of North America', *Arctic*, **39**, 29–38.

Hirano, M. and Antya, M. 1988. 'A rational explanation of cross-profile morphology for glacial valleys and of glacial valley development', *Earth Surface Processes and Landforms*, **13**, 707–716.

Howes, D. E. and Kenk, E. 1988. *Terrain Classification System for British Columbia*, British Columbia Ministry of Environment, MOE Manual **10**, 90 pp.

Hu, X. Q. and Cruden, D. M. 1992a. 'Rock mass movements across bedding in Kananaskis Country, Alberta', *Canadian Geotechnical Journal*, **29**, 675–685.

Hu, X. Q. and Cruden, D. M. 1992b. 'A portable tilting table for on-site tests of the friction angles of discontinuities in rock masses', *International Association of Engineering Geology Bulletin*, **46**, 59–62.

 

Hu, X. Q. and Cruden, D. M. 1993. 'Buckling deformation in the Highwood Pass, Alberta', *Canadian Geotechnical Journal*, **30**, 276–286.

Kane, A. 1992. *Scrambles in the Canadian Rockies*, Rocky Mountain Books, Calgary, Alberta, 208 pp.

Kruszyna R. and Putnam, W. L. 1985. *The Rocky Mountains of Canada – North*, The Alpine Club of Canada, Banff, Alberta, 336 pp.

Leech, G. B. 1979. *Geology, Kananaskis Lakes, West Half. British Columbia and Alberta*, Open File **634**, Geological Survey of Canada, Ottawa.

Luckman, B. H. 1981. 'Geomorphology of the Alberta Rocky Mountains, a review and commentary', *Zeitschrift für Geomorphologie*, Supplement 37, 91–119.

Luckman, B. H. and Fiske, C. J. 1997. 'Holocene development of coarse debris landforms in the Canadian Rockies', *Palaoklimaforschung*, **19**, 277–291.

Mathews, W. H. 1986. *Physiographic Map of the Canadian Cordillera*, Map 1701A, Geological Survey of Canada.

McAffee, R. P. and Cruden, D. M. 1996. 'Landslides at Rock Glacier Site, Highwood Pass, Alberta', *Canadian Geotechnical Journal*, **33**, 685–695.

McMechan, M. E. 1993. *Geology, Rocky Mountain Foothills and Front Ranges in Kananaskis Country, Alberta*, Map 1865A, Geological Survey of Canada, Ottawa.

McMechan, M. E. and Thompson, R. I. 1995. *Geology and structure cross-sections, Jarvis Lakes, British Columbia*, Map 1874A, Geological Survey of Canada, Ottawa.

Mountjoy, E. W. and Price, R. A. 1972a. *Geology, Banff – East Half, Alberta–British Columbia*, Map 1294A, Geological Survey of Canada, Ottawa.

Mountjoy, E. W. and Price, R. A. 1972b. *Geology, Mount Eisenhower – West Half, Alberta*, Map 1297A, Geological Survey of Canada, Ottawa.

Mountjoy, E. W. and Price, R. A. 1988. *Geology, Amethyst Lakes, Alberta–British Columbia*, Map 1657A, Geological Survey of Canada, Ottawa.

Muecke, G. K. and Charlesworth, H. A. K. 1966. 'Jointing in folded Cardium sandstones along the Bow River, Alberta', *Canadian Journal of Earth Sciences*, **3**, 579–596.

Palliser, J. 1863. *The Journals, Detailed Reports and Observations relative to the exploration by Captain Palliser of that portion of British North America which in Latitude lies between the Boundary Line and the Height of Land or Watershed of the Northern or Frozen Ocean respectively, and in Longitude, between the Western Shore of Lake Superior and the Pacific Ocean during the years 1857, 1858, 1859 and 1860*, Her Majesty's Stationery Office, London, 325 pp.

Pole, G. 1992. *Canadian Rockies*, Altitude Publishing, Banff, Alberta, 349 pp.

Powell, J. W. 1875. *Exploration of the Colorado River of the West and its Tributaries*, Government Printing Office, Washington, DC, 291 pp.

Price, R. A. 1970. *Geology, Canmore – West Half, Alberta*, Map 1266A, Geological Survey of Canada, Ottawa.

Price, R. A. and Mountjoy, E. W. 1972. *Geology, Banff – West Half, Alberta – British Columbia*, Map 1295A, Geological Survey of Canada, Ottawa.

Price, R. A., Mountjoy, E. W. and Cook, D. G. 1978. *Geology, Mount Goodsir, East Half. British Columbia and Alberta*, Map 1476A, Geological Survey of Canada, Ottawa.

Price, R. A., Cook, D. G., Aitken, J. D. and Mountjoy, E. W. 1980a. *Geology, Lake Louise, East Half, Alberta and British Columbia*, Map 1483A, Geological Survey of Canada.

Price, R. A., Cook, D. G., Aitken, J. D. and Mountjoy, E. W. 1980b. *Geology, Lake Louise, West Half, British Columbia and Alberta*, Map 1483A, Geological Survey of Canada, Ottawa.

Putnam W. L. and Boles, G. W. 1973. *Climber's Guide to the Rocky Mountains of Canada - South*, Alpine Club of Canada. Banff. Alberta. 330 pp.

Sander, B. 1970. *An Introduction to the Study of the Fabric of Geological Bodies*, Pergamon, Oxford, 641 pp.

Sauchyn, D., Cruden, D. M. and Hu, X. Q. 1998. 'Structural control of rockwall morphometry, Kananaskis region, Canadian Rocky Mountains', *Geomorphology*, **22**, 313–324.

Selby, M. J. 1993. *Hillslope Materials and Processes*, Oxford University Press, Oxford, 451 pp.

Simmons, J. V. and Cruden, D. M. 1980. 'A rock labyrinth in the Front Ranges of the Rockies, Alberta', *Canadian Journal of Earth Sciences*, **17**, 1300–1309.

Strong, W. L. and Leggat, K. R. 1992. *Ecoregions of Alberta*, Alberta Forestry Lands and Wildlife, Edmonton, Publication **T245**, 59 pp.

Taylor, C. G. 1981. 'Fort St. John', in Slaney, V. R. (Ed.), *LANDSAT Images of Canada, A Geological Appraisal*, Geological Survey of Canada, Ottawa, Paper 80–15, 88 pp.

Tricart, J. 1974. *Structural Geomorphology*, Longman, London, 305 pp.

Turner, F. J. and Weiss, L. E. 1963. *Structural Analysis of Metamorphic Tectonites*, McGraw-Hill, New York, 545 pp.

 